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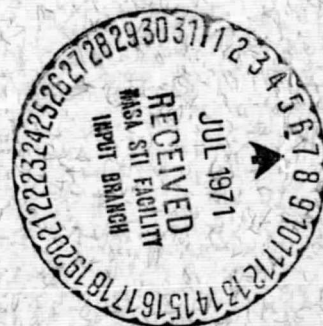
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# RAE-B LAUNCH OPPORTUNITY ANALYSIS

HOBART SWARTWOOD, JR.

RAE-B MISSION ANALYSIS REPORT NO. 1

MAY 1971



**GODDARD SPACE FLIGHT CENTER**  
GREENBELT, MARYLAND

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#### ABSTRACT

Launch opportunities for the Radio Astronomy Explorer-B during the period March through December 1973 are determined. It is assumed that the flight time to the Moon is 110 hours; that all rocket engine burns are impulsive; and that the maximum allowable velocity increment to insert into and circularize the lunar orbit is 0.720 km/sec. Thermal and power requirements constrain the spin axis-Sun angle to be maintained between  $60^\circ$  and  $120^\circ$  throughout the lunar transfer. The circular lunar orbit is required to be inclined  $116.5^\circ$  to the lunar equator; to be at an altitude of 1100 km; and to be entirely in sunlight for at least 50 days. Shadows during the park orbit, injection, and transfer phases are determined. It is shown that imposition of the above assumptions and constraints yields from two to seven launch opportunities per month if no transfer shadows are allowed and no restrictions are placed on park orbit duration or shadows. Most of the prime launch dates have one acceptable launch opportunity, but a few have two. Similarities and differences of the two opportunities are discussed in detail. The effect of varying the launch azimuth and flight time is also examined.

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## RAE-B LAUNCH OPPORTUNITY ANALYSIS

### I. INTRODUCTION

Present plans call for the Radio Astronomy Explorer-B (RAE-B) scientific satellite to be placed into a nearly circular orbit around the Moon. The orbit will be inclined 116.5 degrees to the Moon's equator and will be at an altitude of 1100 km. Proposed launch dates for the mission are during the period March through December 1973. Constraints imposed by thermal and electrical power considerations, by spacecraft gravity gradient utilization considerations, and by on-board propulsion system limitations all serve to limit the number of possible launch dates. It is the purpose of this report to define acceptable launch opportunities in this period which are consistent with these launch and transfer conditions.

For the purpose of this analysis, it is assumed that the launch azimuth is 90 degrees and that no out of plane maneuvers are made. The nominal flight time is assumed to be 110 hours. The effect of varying the launch azimuth and flight time is examined in considerable detail, and comparisons are made.

The spacecraft will be inserted into lunar orbit at closest approach to the Moon via the solid propellant retro motor. The lunar orbit will then be circularized by means of the Velocity Control Propulsion System (VCPS). The sum of these two  $\Delta v$ 's shall be referred to as the velocity increment to attain circular orbit from the approach trajectory ( $\Delta V_c$ ). The maximum allowable  $\Delta V_c$  is currently 0.720 km/sec. After lunar orbit insertion and circularization, the spacecraft will be stabilized in its gravity gradient mode. To assure adequate time for completion of this operation before encountering any lunar shadows, it is desirable that the orbit be totally sunlit for at least 50 days.

The thermal and power requirements through the lunar transfer impose the constraint that the spin axis-Sun angle be maintained between 60° and 120°. It is shown that a considerable number of launch dates are rendered unacceptable under this constraint. Therefore the limits have been extended to 50° to 130° with the realization that a post-injection attitude maneuver may be necessary to achieve operational bounds.

Launch opportunities are also influenced by shadow conditions in the park, injection, and transfer phases of the trajectory. The transfer trajectory shadows

are the most serious as they are generally very lengthy and pose difficulties from thermal and electrical power considerations. Entirely shadow-free trajectories are few, but there are many with no shadows in the transfer phase.

## II. TRAJECTORY CHARACTERISTICS AND GEOMETRY

### A. Computer Program

It has been shown (Ref. 1) that the "multi-conic" method of trajectory generation yields very good agreement with numerical integration programs while requiring only a fraction of the computer time. The Advanced Mission Analysis Program (AMAP) (Ref. 2) was modified to use the multi-conic technique, and that program was used to generate the transfer trajectories for this analysis.

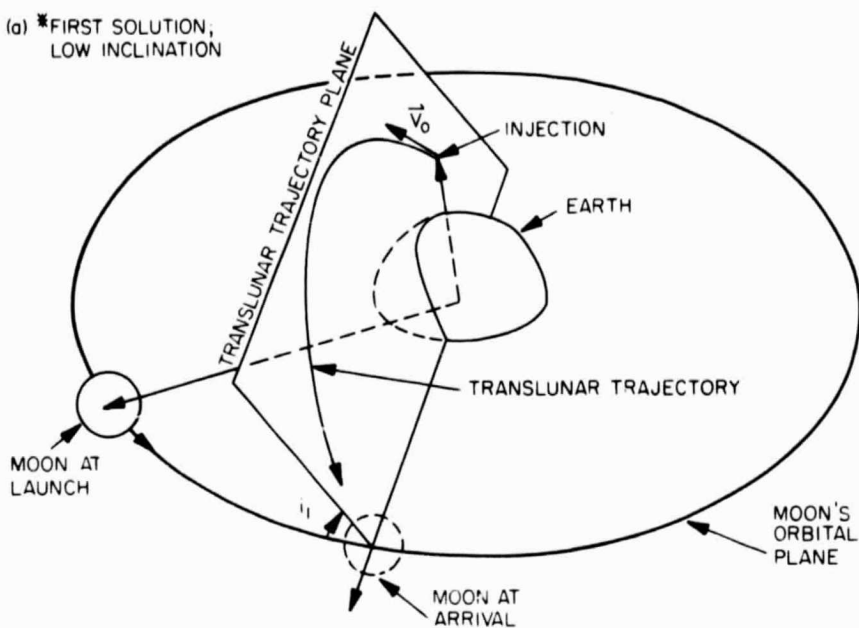
Inputs to AMAP include: launch date, launch azimuth, launch vehicle trajectory geometry, park orbit altitude and the desired target parameters (flight time, perilune radius and inclination of the lunar orbit). The program generates a "first guess" solution based on a geocentric conic trajectory to a massless moon. This guess is then refined through an iterative process to satisfy the target parameters by adjusting launch time, park orbit time and injection velocity. Upon converging to a final targeted trajectory, information relating to the RAE-B constraints is output along with the normal trajectory parameters.

### B. Launch Time

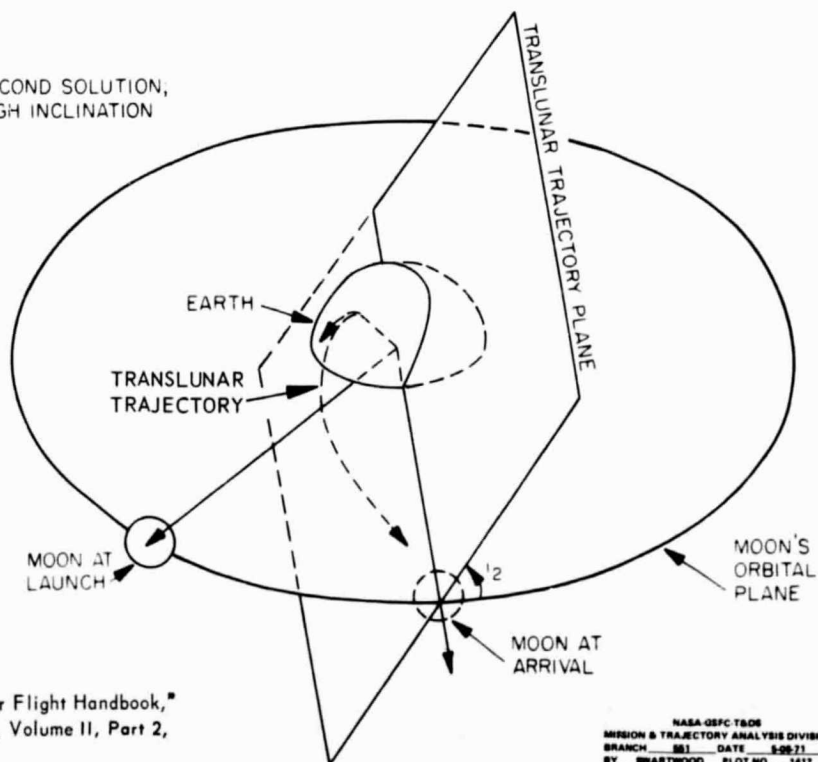
With the assumption that no expensive out-of-plane engine burns are allowed, the park orbit orientation is determined by the launch azimuth and launch time on a given day, and will remain essentially inertially fixed. (Actually, perturbations will cause the orbit to change, but over such short time intervals as the period of the orbit, we can consider the orbit to remain inertially fixed.) Due to errors in the Delta launch vehicle guidance system it is desirable to have a short park orbit coast time, and in all cases it should be less than the period of the park orbit. Under these considerations then we see that to construct a trajectory from Earth to Moon, the park orbit plane must contain the Moon at arrival. Since the park orbit "rotates with the Earth," some time later, within 24 hrs., the park orbit plane will again align itself with the position of the Moon at arrival, and so yielding a total of two launch times per day. This is best illustrated by the accompanying figures. Figure 1(a) depicts a favorable geometry (launch time) for lunar transfer. Figure 1(b) is also a favorable geometry, but is at a different time on the same day.

The two solutions are qualitatively different. Figure 2 shows how the inclination of the transfer trajectory to the Moon's orbit plane varies with launch date for

(a) \*FIRST SOLUTION,  
LOW INCLINATION



(b) SECOND SOLUTION,  
HIGH INCLINATION



\*From "Lunar Flight Handbook,"  
NASA SP34, Volume II, Part 2,  
p. V, 15.

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BRANCH 561 DATE 8-28-71  
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Figure 1. Lunar Transfer Geometry



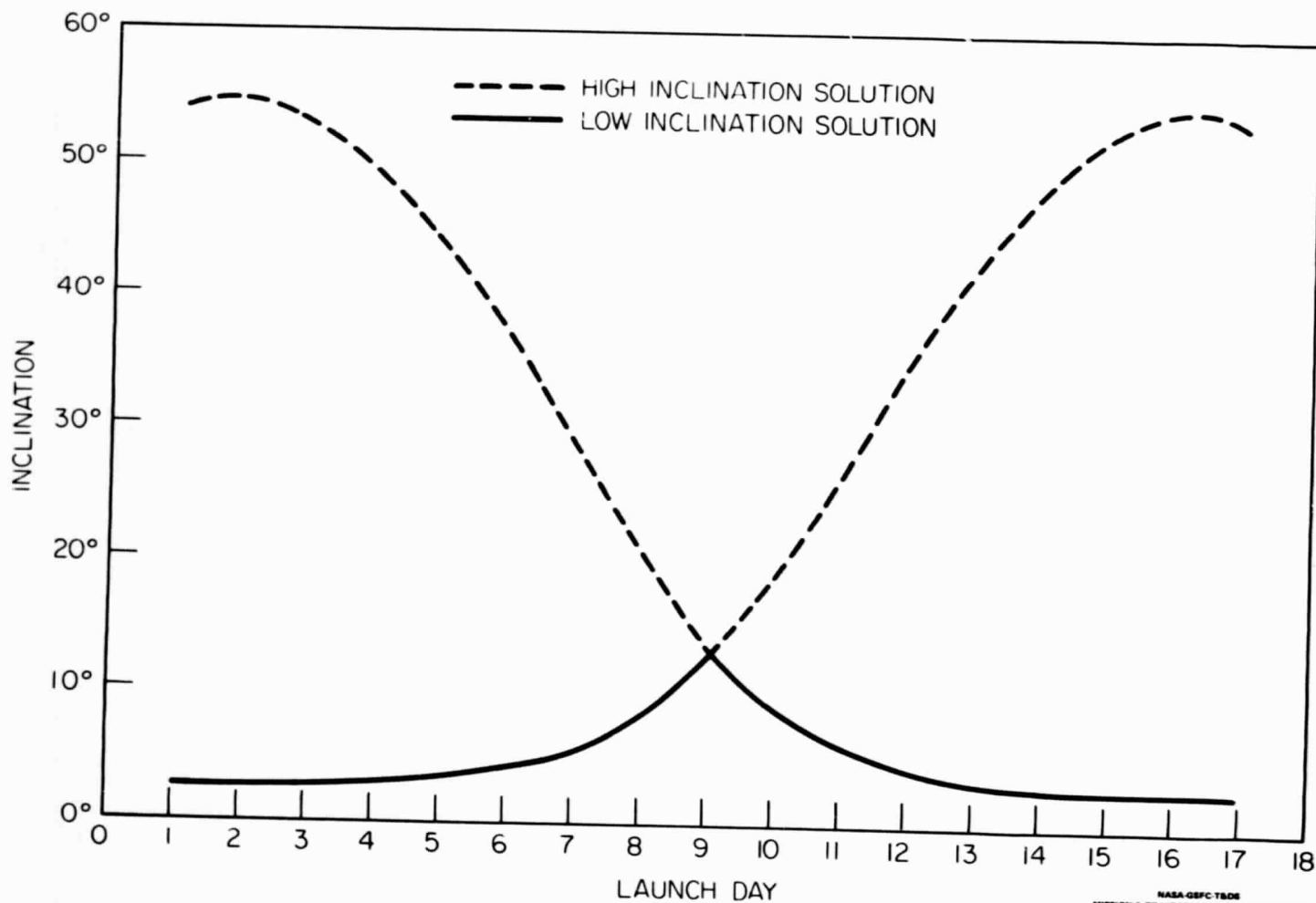


Figure 2. Inclination of Transfer to Moon's Orbit Plane vs Launch Day

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a typical period. Note that on each day there are two solutions. The difference in inclination of the two solutions is a maximum when the Moon is coincident with the intersection of Earth's equator and the Moon's orbital plane, and is a minimum when the Moon is at its maximum and minimum declination relative to the Earth's equator. The two solutions are referred to as "high" and "low" with reference to their inclination. The park orbit coast times are different for the two solutions; the difference varies from essentially zero to about 4500 sec. The high inclination solutions have consistently higher arrival energies ( $C_3$ ) at the Moon, and correspondingly higher velocity increments to circularize the lunar orbit. Thus few of the high inclination transfer trajectories are acceptable, as an upper limit is placed on the  $\Delta V_c$ .

### C. Shadow

Shadows in the park orbit and transfer trajectory can pose problems from the spacecraft power system standpoint. If the park orbit coast time is very long, i.e., greater than about 3/5 of a period, the vehicle will certainly enter shadow in the park orbit, and may remain in shadow for a maximum of about 41 min. For the short coast times, the vehicle may or may not enter shadow depending upon the lunar phase. When launch is during the "new moon" phase, shadows will be unavoidable in the park orbit; when the Moon is near its "full moon" phase, shadows in the transfer trajectory can arise. These shadows can be quite long and pose serious problems from thermal and power considerations and should be avoided.

The shadow times for each date were determined using a precision numerical integration program.

## III. ASSUMPTIONS AND CONSTRAINTS

Acceptable launch dates must be consistent with certain launch and lunar arrival constraints and assumptions. To determine these dates it was assumed that:

- the flight time from translunar injection to closest approach to the Moon is 110 hours,
- all rocket engine burns are impulsive and in-plane,
- the vehicle's spin axis is coincident with its velocity vector at translunar injection,
- the powered flight ascent from the launch pad to park orbit insertion takes 600 sec. and burns through an Earth-fixed central angle of  $21^\circ$ ,

- the park orbit coast time is less than one revolution.

Constraints are imposed on both the launch and the arrival conditions. Thermal and power requirements through the spin stabilized phases of the mission require the spin axis-Sun angle as determined at translunar injection to be maintained between  $60^\circ$  and  $120^\circ$ . This orientation assures an adequate power profile and thermal balance across the spacecraft. This constraint can be relaxed for short periods during the mission. In order to gain a larger number of launch opportunities it was assumed that the bounds can be extended to  $50^\circ$  to  $130^\circ$  at translunar injection, with the realization that a post-injection attitude maneuver may be necessary to establish adequate operational conditions. This sequence will provide additional acceptable launch dates with little compromise.

It has been shown (Ref. 3) that to minimize growth in eccentricity for the RAE-B lunar orbit, the selenographic inclination should be approximately  $116^\circ 5'$ . Thus the lunar orbit is constrained to be initially inclined at  $116^\circ 5'$ , circular, and at an altitude of 1100 km.

The lunar orbit is subject to perturbations primarily from lunar gravitational anomalies and from the Earth. The net result of these effects is to cause a regression of the line of nodes,  $\Omega$ , (the intersection of the orbit plane and the ecliptic plane) of the orbit. Using a numerical integration program including perturbations from presently known lunar gravitational anomalies and the sun and planets, the nodal regression rate can be determined. Then, if we add to this the rate of rotation of the Moon-Sun line, we obtain the net nodal regression rate with respect to the Moon-Sun line. This effect will cause some part of the orbit to be in Moon shadow at times, and sometimes completely in sunlight, see Figure 3. The RAE-B lunar orbit is constrained to be in sunlight at least 50 days for satellite calibration and boom deployment purposes.

During the lunar transfer it will be necessary to make mid-course guidance corrections. Each correction requires some amount of fuel and so the weight of the spacecraft at perilune will vary accordingly. The retro motor for lunar orbit insertion is a solid propellant motor of fixed total impulse. Thus the net velocity increment of which it is capable is a function of spacecraft weight, an unknown quantity. After orbit insertion the on-board hydrazine system (VCPS) will be used for trimming the orbit to make it circular. The maximum allowable velocity increment to circularize the orbit,  $\Delta V_c$  (the sum of the insertion and circularization  $\Delta V$ 's) is currently limited to 0.720 km/sec. This constraint can be affected by changes in spacecraft weight and/or the VCPS fuel margin needed for contingencies.

We can get a qualitative picture of how the launch and arrival constraints vary with launch date for a typical two month period under consideration from Figure 4.

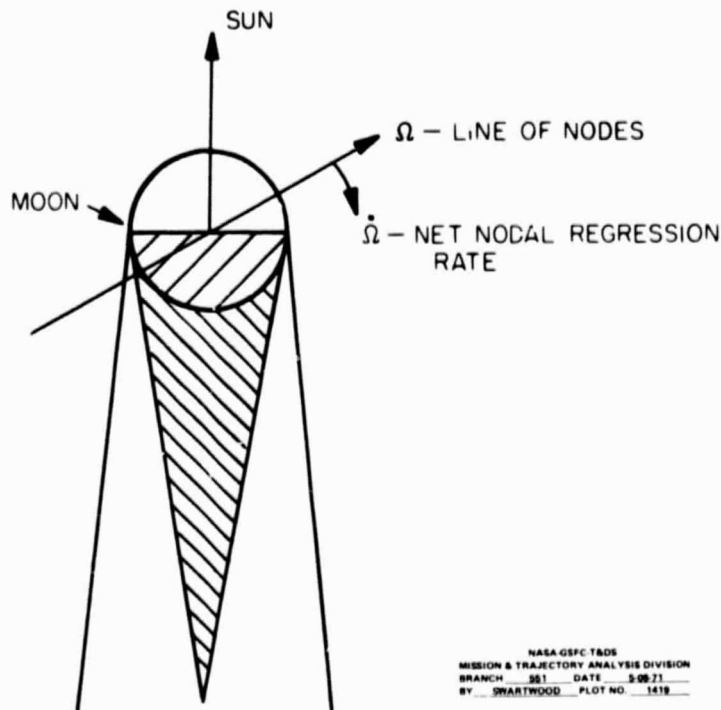


Figure 3. Showing Line of Nodes and Net Nodal Regression Rate Due to Perturbations and Motion About Sun.

The sunlit orbit time varies linearly with launch date up to a maximum of approximately 106 days, at which time the orbit enters shadow, again for a maximum of about 106 days. The spin axis-Sun angle varies from a few degrees (because the transfer trajectory is inclined slightly with respect to the ecliptic plane) up to almost  $180^\circ$  (again, never  $180^\circ$  for the same reason). The circular velocity increment is periodic and varies from about 0.698 km/sec to about 0.743 km/sec. Figure 4 is for the low inclination solution only. The sunlit orbit time and spin axis-Sun angle should not be significantly different for the high inclination solution. The energy curve should vary from slightly higher to significantly higher through a lunar month.

The Moon is in an eccentric orbit about the Earth, and thus, for a fixed flight time, the arrival energy, and thus  $\Delta V_c$ , varies with a period of one lunar month depending upon whether arrival is during lunar perigee or apogee. Notice that the velocity increment constraint is generally satisfied since it is below the upper limit value of 0.720 km/sec most of the time, approximately 18 or 19 days per month.

The spin axis-Sun angle and sunlit orbit time constraints, however, are satisfied for only short periods since their slopes are so great. In May, for example, the

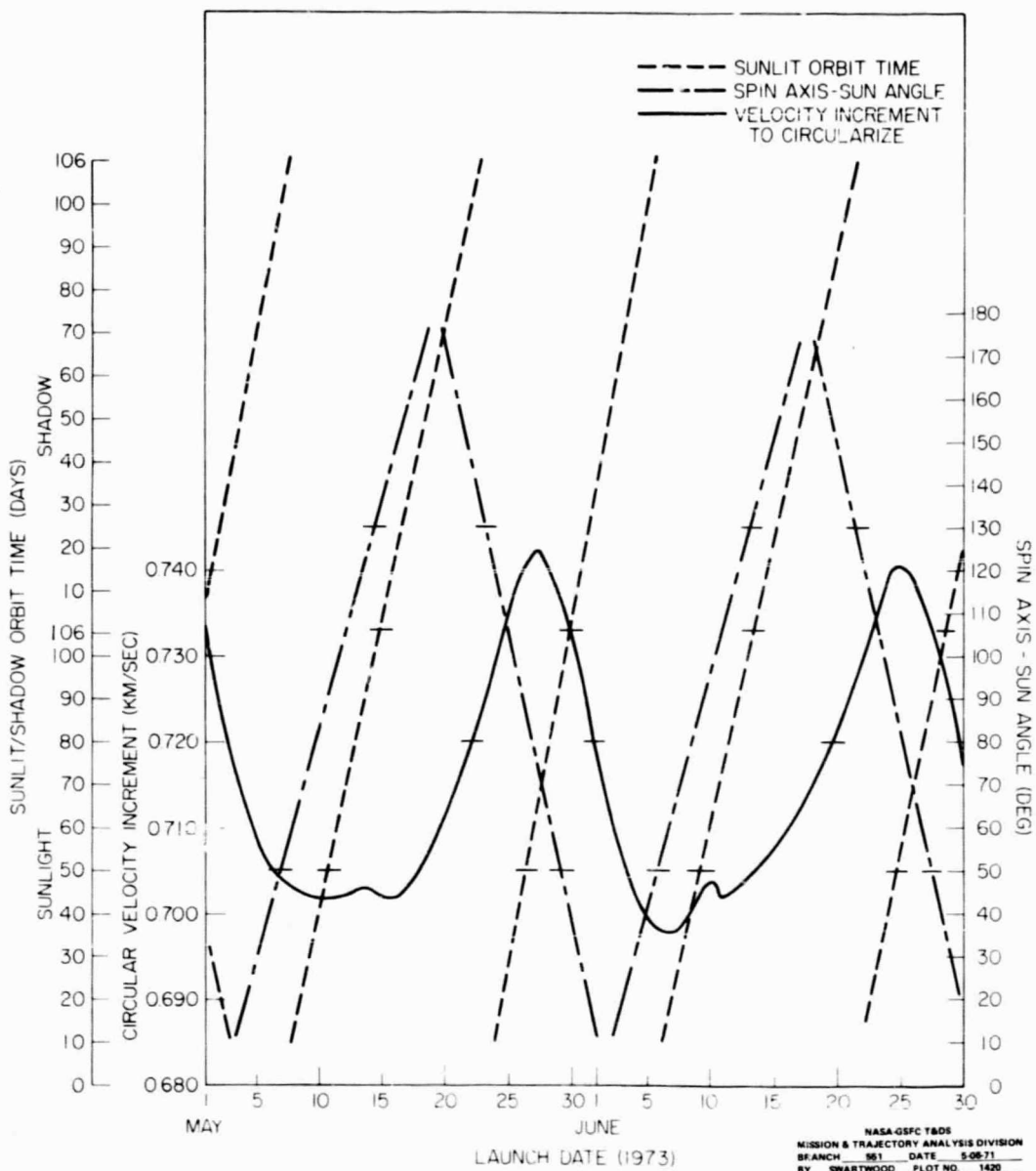


Figure 4. RAE-B Launch and Arrival Constraints vs Launch Date

velocity increment requirement is satisfied from May 4 through May 22; the spin axis-Sun angle requirement is satisfied May 7 through May 14, the sunlit orbit time from May 11 through May 14. The only period when all are satisfied is May 11 through May 14. Continuing in this fashion, one can generate acceptable launch dates for the entire period under consideration. The possibility of shadows in the park orbit and transfer trajectory must now be considered.

#### IV. RESULTS

If all the assumptions and constraints which are considered in this study are imposed, then only a few days in the March to December 1973 launch period comply. Table I gives the acceptable dates with their corresponding launch and arrival parameters neglecting any shadow constraints. Recall that a 90° launch azimuth and a 110 hour flight time were assumed. Certain of the columns in Table I deserve some explanation. Launch time, Park Orbit Coast Time, and Spin Axis-Sun Angle are self-explanatory. Shadow time is divided into three logical sections: Park – the duration of shadow during the park orbit coast; Injection – the duration in shadow in the transfer from injection to shadow exit; Transfer – shadow time during the transfer trajectory. The Lunar Phase Angle at Arrival is the angle measured from the Moon-Earth line to the Moon-Sun line. This angle is 0 degrees at full Moon and 180 degrees at new Moon. Sunlit Orbit Time is the total time after lunar orbit insertion that the orbit will be in complete sunlight.  $\Delta V$  for Circular Orbit is self-explanatory.

Table II also deserves some comment. The inclination of an orbit is defined by the mathematical relation

$$i = \cos^{-1} \frac{(\vec{r} \times \vec{v} \cdot \hat{z})}{|\vec{r} \times \vec{v}|}$$

where,

$\vec{r}$  = position vector of the spacecraft,

$\vec{v}$  = velocity vector of the spacecraft,

$\hat{z}$  = unit normal to the reference plane.

It is seen in Figure 5 that two possible approach trajectories yield the same inclination. These are referred to as "northern" and "southern" with respect to the lunar equator. The normal to the plane can be represented by its spherical

**Table I**  
**Launch and Arrival Parameters**

| Launch Date | Launch Time (GMT) | Park Orbit Coast Time (sec) | Spin Axis-Sun Angle (deg) | Shadow Time |                 |                | Lunar Phase Angle At Arrival (deg) | Sunlit Orbit Time (days) | $\Delta V$ for Circular Orbit (km/sec) |
|-------------|-------------------|-----------------------------|---------------------------|-------------|-----------------|----------------|------------------------------------|--------------------------|--|
|             |                   |                             |                           | Park (min)  | Injection (min) | Transfer (hrs) |                                    |                          |  |
| 3-13-73     | 23:20             | 3703                        | 94                        | 37          | 0               | 0              | - 4                                | 53                       | 0.713                                  |
| -14-        | 23:23             | 3876                        | 106                       | 37          | 0               | 0              | - 8                                | 68                       | 0.711                                  |
| -15-        | 23:27             | 4042                        | 118                       | 37          | 0               | 4.3            | 19                                 | 84                       | 0.709                                  |
| -16-        | 23:33             | 4196                        | 130                       | 36          | 0               | 2.7            | 31                                 | 99                       | 0.706                                  |
| 4-11-73     | 21:38             | 3979                        | 87                        | 41          | 0               | 0              | - 12                               | 47                       | 0.707                                  |
| -12-        | 21:43             | 4136                        | 98                        | 41          | 0               | 0              | 0                                  | 63                       | 0.706                                  |
| -13-        | 21:52             | 4279                        | 110                       | 41          | 0               | 4.8            | 11                                 | 78                       | 0.705                                  |
| -14-        | 22:06             | 4402                        | 121                       | 41          | 0               | 4.1            | 22                                 | 92                       | 0.703                                  |
| -14-        | 16:04             | 279                         | 111                       | 0           | 0               | 0              | 19                                 | 84                       | 0.716                                  |
| -15-        | 17:23             | 179                         | 123                       | 0           | 0               | 0              | 31                                 | 100                      | 0.709                                  |
| 5-11-73     | 20:14             | 4358                        | 91                        | 41          | 0               | 0              | - 8                                | 57                       | 0.702                                  |
| -12-        | 20:34             | 4458                        | 102                       | 41          | 0               | 11.2           | 3                                  | 72                       | 0.703                                  |
| -12-        | 15:07             | 215                         | 97                        | 0           | 0               | 0              | 17                                 | 64                       | 0.711                                  |
| -13-        | 21:08             | 4511                        | 113                       | 41          | 0               | 5.6            | 14                                 | 86                       | 0.703                                  |
| -13-        | 16:16             | 148                         | 108                       | 0           | 0               | 0              | 18                                 | 79                       | 0.706                                  |
| -14-        | 17:08             | 143                         | 120                       | 0           | 0               | 0              | 23                                 | 94                       | 0.703                                  |
| -14-        | 22:00             | 4503                        | 123                       | 41          | 0               | 0              | 19                                 | 101                      | 0.706                                  |
| 6-09-73     | 19:09             | 4493                        | 83                        | 41          | 0               | 0              | - 15                               | 51                       | 0.701                                  |
| -10-        | 19:55             | 4506                        | 94                        | 41          | 0               | 0              | - 4                                | 66                       | 0.704                                  |
| -10-        | 15:03             | 144                         | 91                        | 0           | 0               | 0              | - 7                                | 58                       | 0.703                                  |
| -11-        | 15:42             | 180                         | 103                       | 0           | 0               | 0              | 4                                  | 73                       | 0.702                                  |
| -11-        | 20:58             | 4457                        | 105                       | 41          | 0               | 0              | 7                                  | 81                       | 0.709                                  |
| -12-        | 16:05             | 265                         | 114                       | 0           | 0               | 0              | 15                                 | 86                       | 0.703                                  |
| -12-        | 22:13             | 4360                        | 113                       | 40          | 0               | 0              | 18                                 | 95                       | 0.716                                  |
| -13-        | 16:20             | 381                         | 125                       | 0           | 0               | 2.5            | 26                                 | 99                       | 0.705                                  |
| 7-09-73     | 14:09             | 239                         | 85                        | 0           | 0               | 0              | - 14                               | 52                       | 0.701                                  |
| -10-        | 14:26             | 345                         | 96                        | 0           | 0               | 0              | - 3                                | 65                       | 0.703                                  |
| -11-        | 14:37             | 474                         | 107                       | 0           | 0               | 11.4           | 9                                  | 78                       | 0.706                                  |
| -12-        | 14:44             | 617                         | 118                       | 0           | 0               | 5.0            | 19                                 | 91                       | 0.709                                  |
| -13-        | 14:49             | 769                         | 129                       | 0           | 0               | 2.8            | 31                                 | 104                      | 0.712                                  |
| 8-08-73     | 12:53             | 568                         | 88                        | 0           | 0               | 0              | - 11                               | 55                       | 0.706                                  |
| -09-        | 12:59             | 717                         | 99                        | 0           | 0               | 0              | 1                                  | 68                       | 0.710                                  |
| -10-        | 13:03             | 874                         | 111                       | 0           | 0               | 0              | 12                                 | 81                       | 0.714                                  |
| -11-        | 13:06             | 1125                        | 122                       | 0           | 0               | 0              | 24                                 | 94                       | 0.714                                  |

Table I-(continued)

| Launch Date | Launch Time (GMT) | Park Orbit Coast Time (sec) | Spin Axis-Sun Angle (deg) | Shadow Time |                  |                | Lunar Phase Angle At Arrival (deg) | Sunlit Orbit Time (days) | $\Delta V$ for Circular Orbit (km/sec) |
|-------------|-------------------|-----------------------------|---------------------------|-------------|------------------|----------------|------------------------------------|--------------------------|--|
|             |                   |                             |                           | Park (min)  | Injec-tion (min) | Transfer (hrs) |                                    |                          |  |
| 9-06-73     | 11:13             | 813                         | 80                        | 0           | 0                | 0              | - 19                               | 45                       | 0.711                                  |
| -07-        | 11:17             | 973                         | 92                        | 0           | 0                | 0              | - 7                                | 57                       | 0.715                                  |
| -08-        | 11:21             | 1140                        | 104                       | 0           | 0                | 0              | 5                                  | 70                       | 0.720                                  |
| -09-        | 11:25             | 1397                        | 116                       | 0           | 0                | 0              | 18                                 | 83                       | 0.720                                  |
| -22-        | 10:51             | 3916                        | 76                        | 24          | 9                | 0              | -174                               | 64                       | 0.718                                  |
| -23-        | 10:58             | 4080                        | 63                        | 27          | 7                | 0              | -161                               | 80                       | 0.715                                  |
| -24-        | 11:08             | 4225                        | 51                        | 30          | 5                | 0              | -149                               | 96                       | 0.711                                  |
| 10-21-73    | 9:16              | 4165                        | 83                        | 22          | 10               | 0              | 179                                | 59                       | 0.710                                  |
| -22-        | 9:30              | 4299                        | 71                        | 25          | 8                | 0              | -170                               | 74                       | 0.708                                  |
| -23-        | 9:51              | 4404                        | 59                        | 28          | 6                | 0              | -158                               | 90                       | 0.706                                  |
| 11-19-73    | 7:55              | 4365                        | 91                        | 25          | 11               | 0              | 170                                | 53                       | 0.703                                  |
| -20-        | 8:24              | 4442                        | 79                        | 26          | 9                | 0              | -178                               | 68                       | 0.703                                  |
| -21-        | 9:07              | 4468                        | 69                        | 27          | 8                | 0              | -167                               | 84                       | 0.704                                  |
| -22-        | 4:36              | 203                         | 61                        | 3           | 7                | 0              | -159                               | 90                       | 0.702                                  |
| -23-        | 5:04              | 274                         | 50                        | 5           | 5                | 0              | -148                               | 105                      | 0.702                                  |
| 12-18-73    | 7:04              | 4459                        | 99                        | 27          | 12               | 0              | 162                                | 47                       | 0.701                                  |
| -19         | 2:33              | 197                         | 91                        | 3           | 11               | 0              | 170                                | 52                       | 0.700                                  |
| -20-        | 3:07              | 251                         | 80                        | 4           | 9                | 0              | -179                               | 68                       | 0.700                                  |
| -21-        | 3:28              | 344                         | 69                        | 6           | 8                | 0              | -168                               | 82                       | 0.701                                  |
| -22-        | 3:41              | 461                         | 58                        | 8           | 6                | 0              | -157                               | 95                       | 0.703                                  |

components, and serves to orient the planet inertially. The spherical components are its right ascension, measured from Aries, and its declination, measured from Earth's equator. Table II gives the spherical celestial coordinates of the orbit normal for each launch date in Table I.

All the launch and arrival parameters listed are for the northern approach except for the last two columns in Table II which are for the southern approach. The southern approach involves only a small change in launch time and park time; all the other parameters should remain essentially the same.

Notice that the number of launch dates per month varies from only 3 in October, to 7 in September. On some days there are two launch opportunities, one with the high inclination transfer, and one with the low. The two solutions differ



Table II

| Launch Date | Celestial Coordinates of Orbit Normal |                        |                   |                   | Launch Date | Celestial Coordinates of Orbit Normal |                   |                   |                   |
|-------------|---------------------------------------|------------------------|-------------------|-------------------|-------------|---------------------------------------|-------------------|-------------------|-------------------|
|             | Northern Approach                     |                        | Southern Approach |                   |             | Northern Approach                     |                   | Southern Approach |                   |
|             | $\alpha^{\dagger}$<br>(deg)           | $\delta^{**}$<br>(deg) | $\alpha$<br>(deg) | $\delta$<br>(deg) |             | $\alpha$<br>(deg)                     | $\delta$<br>(deg) | $\alpha$<br>(deg) | $\delta$<br>(deg) |
| 3-13-73     | 166.9                                 | -21.7                  | 10.1              | -26.3             | 7-09-73     | 300.8                                 | -48.0             | 107.5             | - 3.9             |
| -14-        | 180.0                                 | -27.4                  | 21.8              | -21.3             | -10-        | 316.4                                 | -45.2             | 118.3             | - 5.5             |
| -15-        | 193.8                                 | -33.2                  | 33.1              | -16.6             | -11-        | 330.0                                 | -41.7             | 128.9             | - 7.9             |
| -16-        | 208.6                                 | -38.7                  | 44.3              | -10.2             | -12-        | 341.1                                 | -37.7             | 139.5             | -10.0             |
| 4-11-73     | 189.6                                 | -31.5                  | 29.6              | -18.0             | -13-        | 353.2                                 | -33.5             | 144.0             | -14.7             |
| -12-        | 203.9                                 | -37.0                  | 40.7              | -13.6             | 8-08-73     | 337.9                                 | -39.2             | 135.8             | - 9.8             |
| -13-        | 219.2                                 | -42.0                  | 51.7              | -10.0             | -09-        | 349.3                                 | -25.1             | 146.2             | -13.3             |
| -14-        | 236.0                                 | -46.1                  | 62.7              | - 7.0             | -10-        | 359.9                                 | -30.8             | 156.7             | -17.4             |
| -14-        | 226.7                                 | -44.0                  | 63.4              | - 6.8             | -11-        | 10.0                                  | -26.4             | 161.1             | -22.0             |
| -15-        | 245.0                                 | -47.6                  | 74.3              | - 4.8             | 9-06-73     | 355.9                                 | -32.5             | 152.7             | -15.7             |
| 5-11-73     | 230.1                                 | -45.0                  | 59.4              | - 7.8             | -07-        | 6.1                                   | -28.1             | 163.3             | -20.1             |
| -12-        | 248.6                                 | -48.1                  | 70.4              | - 5.4             | -08-        | 15.9                                  | -23.8             | 174.1             | -24.8             |
| -12-        | 239.2                                 | -46.7                  | 70.9              | - 5.3             | -09-        | 25.7                                  | -19.6             | 184.0             | -29.8             |
| -13-        | 267.4                                 | -49.6                  | 81.3              | - 3.9             | -22-        | 181.2                                 | -28.1             | 22.2              | -21.0             |
| -13-        | 258.1                                 | -49.1                  | 81.8              | - 3.8             | -23-        | 195.9                                 | -34.1             | 33.8              | -16.2             |
| -14-        | 277.1                                 | -49.7                  | 92.6              | - 3.3             | -24-        | 211.4                                 | -39.8             | 45.4              | -11.8             |
| -14-        | 286.3                                 | -49.3                  | 92.2              | - 3.3             | 10-22-73    | 206.2                                 | -38.0             | 41.5              | -13.2             |
| 6-09-73     | 261.8                                 | -49.4                  | 77.9              | - 4.2             | -22-        | 222.3                                 | -43.1             | 52.9              | - 9.4             |
| -10-        | 280.7                                 | -49.6                  | 88.9              | - 3.3             | -23-        | 240.1                                 | -47.1             | 64.4              | - 6.4             |
| -10-        | 271.3                                 | -49.7                  | 89.3              | - 3.3             | 11-19-73    | 234.7                                 | -46.1             | 61.0              | - 7.1             |
| -11-        | 289.5                                 | -49.1                  | 100.2             | - 3.4             | -20-        | 253.3                                 | -48.9             | 72.4              | - 4.8             |
| -11-        | 299.1                                 | -48.1                  | 99.7              | - 3.4             | -21-        | 273.0                                 | -50.0             | 83.8              | - 3.4             |
| -12-        | 306.1                                 | -47.1                  | 111.0             | - 4.4             | -22-        | 281.9                                 | -49.8             | 95.6              | - 3.0             |
| -12-        | 316.0                                 | -45.2                  | 110.6             | - 4.3             | -23-        | 299.8                                 | -48.3             | 107.1             | - 3.7             |
| -13-        | 320.9                                 | -44.1                  | 121.8             | - 6.2             | 12-18-73    | 267.3                                 | -49.9             | 80.5              | - 3.6             |
|             |                                       |                        |                   |                   | -19-        | 276.3                                 | -50.0             | 92.3              | - 3.0             |
|             |                                       |                        |                   |                   | -20-        | 294.5                                 | -49.0             | 103.6             | - 3.3             |
|             |                                       |                        |                   |                   | -21-        | 310.9                                 | -46.5             | 114.9             | - 4.7             |
|             |                                       |                        |                   |                   | -22-        | 325.4                                 | -43.2             | 125.9             | - 6.9             |

\* - Right Ascension

\*\* - Declination

 $\dagger$  - Right Ascension Rate is Approximately +0.14 deg/day.

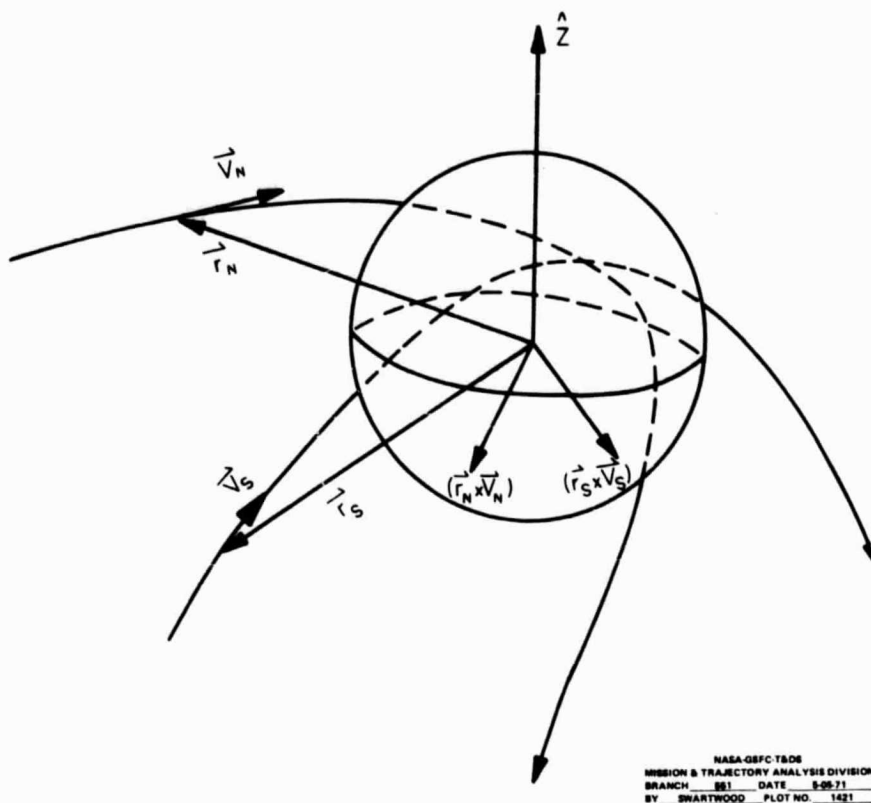


Figure 5. Northern and Southern  
Lunar Approach Trajectories

greatly in their park orbit coast time, and their shadow time. In addition, the high inclination solution requires a higher velocity increment for lunar orbit circularization. The difference in sunlit orbit time is typically 8 or 9 days.

Shadow in the transfer trajectory is a limiting factor in March, April, May, and July. There are no transfer shadows in June. From Table I we see that from August through December, there are no transfer shadows, and relatively short park and injection shadows. The park shadows in the early months vary from about 36 min. to the maximum possible, 41 min. Notice that a few dates have no shadow at all.

Flight times between 100 hours and 120 hours are needed to minimize VCPS propellant requirements. Thus, 110 hours was arbitrarily chosen as a typical flight time to conduct the study. The 90 degree launch azimuth was selected to maximize payload capability. The effect of varying these two parameters can be obtained from an analysis of Tables III, IV, V, VI and VII for the typical launch

Table III

| 7-09-73     |                      | Launch Time (GMT) | Park Orbit Coast Time (sec) | Spin Axis Sun Angle (deg) | Shadow Time Injection |                 |                | Lunar Phase Angle (deg) | Sunlit Orbit Time (days) | $\Delta V$ for Circular Orbit (km/sec) |
|-------------|----------------------|-------------------|-----------------------------|---------------------------|-----------------------|-----------------|----------------|-------------------------|--------------------------|--|
| Flight Time | Launch Azimuth (deg) |                   |                             |                           | Park (min)            | Injection (min) | Transfer (hrs) |                         |                          |  |
| 90 hrs      | 70                   | 10:12             | 861                         | 77                        | 0                     | 0               | 0              | -25                     | 56                       | 0.741                                  |
|             | 90                   | 13:43             | 212                         | 77                        | 0                     | 0               | 0              | -24                     | 59                       | 0.737                                  |
|             | 110                  | 15:23             | 5208                        | 79                        | 41                    | 0               | 0              | -22                     | 60                       | 0.741                                  |
| 110 hrs     | 70                   | 10:47             | 861                         | 84                        | 0                     | 0               | 0              | -16                     | 48                       | 0.704                                  |
|             | 90                   | 14:09             | 239                         | 85                        | 0                     | 0               | 0              | -14                     | 52                       | 0.701                                  |
|             | 110                  | 15:55             | 5216                        | 86                        | 41                    | 0               | 0              | -13                     | 52                       | 0.704                                  |
| 130 hrs     | 70                   | 11:14             | 894                         | 92                        | 0                     | 0               | 0              | - 7                     | 45                       | 0.700                                  |
|             | 90                   | 14:27             | 300                         | 93                        | 0                     | 0               | 0              | - 5                     | 47                       | 0.698                                  |
|             | 110                  | 16:21             | 5255                        | 94                        | 41                    | 0               | 0              | - 4                     | 48                       | 0.701                                  |

Table IV

| 7-10-73     |                      | Launch Time (GMT) | Park Orbit Coast Time (sec) | Spin Axis Sun Angle (deg) | Shadow Time Injection |                 |                | Lunar Phase Angle (deg) | Sunlit Orbit Time (days) | $\Delta V$ for Circular Orbit (km/sec) |
|-------------|----------------------|-------------------|-----------------------------|---------------------------|-----------------------|-----------------|----------------|-------------------------|--------------------------|--|
| Flight Time | Launch Azimuth (deg) |                   |                             |                           | Park (min)            | Injection (min) | Transfer (hrs) |                         |                          |  |
| 90 hrs      | 70                   | 10:48             | 907                         | 87                        | 0                     | 0               | 0              | -14                     | 70                       | 0.742                                  |
|             | 90                   | 14:09             | 287                         | 88                        | 0                     | 0               | 0              | -13                     | 73                       | 0.739                                  |
|             | 110                  | 15:56             | 5263                        | 90                        | 41                    | 0               | 0              | -11                     | 73                       | 0.742                                  |
| 110 hrs     | 70                   | 11:15             | 935                         | 94                        | 0                     | 0               | 0              | - 5                     | 62                       | 0.705                                  |
|             | 90                   | 14:26             | 345                         | 96                        | 0                     | 0               | 0              | - 3                     | 65                       | 0.703                                  |
|             | 110                  | 16:21             | 5296                        | 97                        | 41                    | 0               | 0              | - 2                     | 65                       | 0.706                                  |
| 130 hrs     | 70                   | 11:36             | 988                         | 102                       | 0                     | 0               | 17.5           | 5                       | 58                       | 0.703                                  |
|             | 90                   | 14:39             | 426                         | 104                       | 0                     | 0               | 14.7           | 6                       | 61                       | 0.701                                  |
|             | 110                  | 16:40             | 56                          | 105                       | 0                     | 0               | 12.0           | 7                       | 61                       | 0.703                                  |

Table V

| 7-11-73     |                       | Launch Time (GMT) | Park Orbit Coast Time (sec) | Spin Axis Sun Angle (deg) | Shadow Time Injection |                  |                | Lunar Phase Angle (deg) | Sunlit Orbit Time (days) | $\Delta V$ for Circular Orbit (km/sec) |
|-------------|-----------------------|-------------------|-----------------------------|---------------------------|-----------------------|------------------|----------------|-------------------------|--------------------------|--|
| Flight Time | Launch Azi-muth (deg) |                   |                             |                           | Park (min)            | Injec-tion (min) | Transfer (hrs) |                         |                          |  |
| 90 hrs      | 70                    | 11:15             | 984                         | 98                        | 0                     | 0                | 0              | - 3                     | 83                       | 0.743                                  |
|             | 90                    | 14:25             | 397                         | 99                        | 0                     | 0                | 2.9            | - 1                     | 86                       | 0.741                                  |
|             | 110                   | 16:21             | 5346                        | 100                       | 41                    | 0                | 15.0           | 0                       | 87                       | 0.744                                  |
| 110 hrs     | 70                    | 11:36             | 1032                        | 105                       | 0                     | 0                | 12.5           | 7                       | 75                       | 0.707                                  |
|             | 90                    | 14:37             | 474                         | 107                       | 0                     | 0                | 11.4           | 8                       | 78                       | 0.706                                  |
|             | 110                   | 16:40             | 99                          | 107                       | 0                     | 0                | 9.3            | 9                       | 78                       | 0.708                                  |
| 130 hrs     | 70                    | 11:53             | 1100                        | 113                       | 0                     | 0                | 4.1            | 16                      | 71                       | 0.705                                  |
|             | 90                    | 14:46             | 568                         | 115                       | 0                     | 0                | 6.0            | 17                      | 74                       | 0.704                                  |
|             | 110                   | 16:56             | 170                         | 116                       | 0                     | 0                | 3.7            | 18                      | 74                       | 0.706                                  |

Table VI

| 7-12-73     |                       | Launch Time (GMT) | Park Orbit Coast Time (sec) | Spin Axis Sun Angle (deg) | Shadow Time Injection |                  |                | Lunar Phase Angle (deg) | Sunlit Orbit Time (days) | $\Delta V$ for Circular Orbit (km/sec) |
|-------------|-----------------------|-------------------|-----------------------------|---------------------------|-----------------------|------------------|----------------|-------------------------|--------------------------|--|
| Flight Time | Launch Azi-muth (deg) |                   |                             |                           | Park (min)            | Injec-tion (min) | Transfer (hrs) |                         |                          |  |
| 90 hrs      | 70                    | 11:35             | 1083                        | 108                       | 0                     | 0                | 9.5            | 8                       | 98                       | 0.745                                  |
|             | 90                    | 14:35             | 528                         | 110                       | 0                     | 0                | 8.9            | 10                      | 99                       | 0.743                                  |
|             | 110                   | 16:39             | 152                         | 111                       | 0                     | 0                | 7.5            | 11                      | 99                       | 0.745                                  |
| 110 hrs     | 70                    | 11:52             | 1145                        | 116                       | 0                     | 0                | 4.0            | 18                      | 88                       | 0.710                                  |
|             | 90                    | 14:44             | 617                         | 118                       | 0                     | 0                | 5.0            | 19                      | 91                       | 0.709                                  |
|             | 110                   | 16:55             | 216                         | 118                       | 0                     | 0                | 3.5            | 20                      | 91                       | 0.710                                  |
| 130 hrs     | 70                    | 12:07             | 1223                        | 125                       | 0                     | 0                | 2.5            | 27                      | 84                       | 0.709                                  |
|             | 90                    | 14:51             | 718                         | 126                       | 0                     | 0                | 3.1            | 29                      | 86                       | 0.708                                  |
|             | 110                   | 17:10             | 295                         | 127                       | 0                     | 0                | 2.3            | 30                      | 87                       | 0.709                                  |

Table VII

| 7-13-73     |                      | Launch Time (GMT) | Park Orbit Coast Time (sec) | Spin Axis Sun Angle (deg) | Shadow Time Injection |                 |                | Lunar Phase Angle (deg) | Sunlit Orbit Time (days) | $\Delta V$ for Circular Orbit (km/sec) |
|-------------|----------------------|-------------------|-----------------------------|---------------------------|-----------------------|-----------------|----------------|-------------------------|--------------------------|--|
| Flight Time | Launch Azimuth (deg) |                   |                             |                           | Park (min)            | Injection (min) | Transfer (hrs) |                         |                          |  |
| 90 hrs      | 70                   | 11:51             | 1198                        | 120                       | 0                     | 0               | 3.7            | 20                      | - 3                      | 0.746                                  |
|             | 90                   | 14:42             | 673                         | 121                       | 0                     | 0               | 4.2            | 21                      | - 5                      | 0.745                                  |
|             | 110                  | 16:54             | 269                         | 122                       | 0                     | 0               | 3.3            | 22                      | - 6                      | 0.746                                  |
| 110 hrs     | 70                   | 12:06             | 1270                        | 127                       | 0                     | 0               | 2.4            | 30                      | - 5                      | 0.712                                  |
|             | 90                   | 14:49             | 769                         | 129                       | 0                     | 0               | 2.8            | 31                      | 103                      | 0.711                                  |
|             | 110                  | 17:08             | 342                         | 130                       | 0                     | 0               | 2.2            | 32                      | 104                      | 0.713                                  |
| 130 hrs     | 70                   | 12:19             | 1355                        | 136                       | 0                     | 0               | 1.4            | 39                      | 97                       | 0.712                                  |
|             | 90                   | 14:55             | 875                         | 138                       | 0                     | 0               | 1.9            | 40                      | 100                      | 0.711                                  |
|             | 110                  | 17:22             | 428                         | 138                       | 0                     | 0               | 1.6            | 41                      | 100                      | 0.712                                  |

period July 9 through July 13. The launch and arrival parameters for flight times of 90 hours, 110 hours, and 130 hours and launch azimuths of  $70^\circ$ ,  $90^\circ$  and  $110^\circ$  are compared for each launch date. Notice that for a given launch date and flight time, the park orbit coast time decreases with launch azimuth. For a given launch azimuth, the park orbit coast time increases with flight time. Perhaps the most important observation is that the  $\Delta V_c$  requirement for the 90 hour flight time is consistently much greater than that for the longer flights, and in this period at least, it is prohibitively high.

## V. CONCLUSIONS

Summarily, then, Table I gives all acceptable launch opportunities neglecting the constraint of no shadow in the translunar phase and short park orbit coasts. These two constraints limit the realm of possibilities. If compromises are made though, there exist several launch opportunities per month. Shorter flight times pose the problem of excessive velocity increments to circularize the lunar orbit.

For the time period from March through December 1973, the following table, Table VIII, summarizes the available launch dates for various levels of constraints.

Table VIII  
Number of Days Meeting Constraints

| Month<br>1973 | Spin Axis - Sun Angle<br>+ Sunlit Orbit Time<br>+ Arrival Energy | Plus No<br>Transfer<br>Traj. Shadows | Plus Short<br>Park Orbit<br>Coast | Plus No<br>Park Orbit<br>Shadow |
|---------------|--|--------------------------------------|-----------------------------------|---------------------------------|
| March         | 4  | 2                                    | 0                                 | 0                               |
| April         | 5  | 4                                    | 2                                 | 2                               |
| May           | 4  | 4                                    | 3                                 | 3                               |
| June          | 5  | 5                                    | 4                                 | 4                               |
| July          | 5  | 2                                    | 2                                 | 2                               |
| August        | 4  | 4                                    | 4                                 | 4                               |
| September     | 7 (2 periods)  | 7                                    | 4                                 | 4                               |
| October       | 3  | 3                                    | 0                                 | 0                               |
| November      | 5  | 5                                    | 2                                 | 0                               |
| December      | 5  | 5                                    | 4                                 | 0                               |

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